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LUNAR PHYSICAL PARAMETERS STUDY

PARTIAL REPORT No. 6

FEASIBILITY STUDY

OF

DOWNHOLE LOGGING TOOL

December 12, 1960

TEXACO
INC.

RESEARCH AND TECHNICAL DEPARTMENT

EXPLORATION AND PRODUCTION RESEARCH DIVISION

BELLAIRE, TEXAS

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I. Introduction

A feasibility study has been made of a downhole logging tool designed to measure the density, integral acoustic velocity, temperature, diffusivity, magnetic susceptibility and electrical resistivity of the material adjacent to a hole in the lunar surface. This report covers a study on each of the above items. The assumption was first made that a consolidated, though not necessarily uniform, borehole was available. Modifications necessary for the condition of unconsolidated material where the probe is forced into the material are considered in general but not in detail.

II. Individual Measurements

A. Density Measuring Device

A downhole density measuring device which is feasible would be quite similar to the surface density measuring device described in Texaco's Partial Report No. 1, August 31, 1960, concerning the surface density measurements. In this report, it was shown that the electron density may be measured using a gamma radiation source and a gamma radiation detector.

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The basic geometry would be as shown in Figure 1.

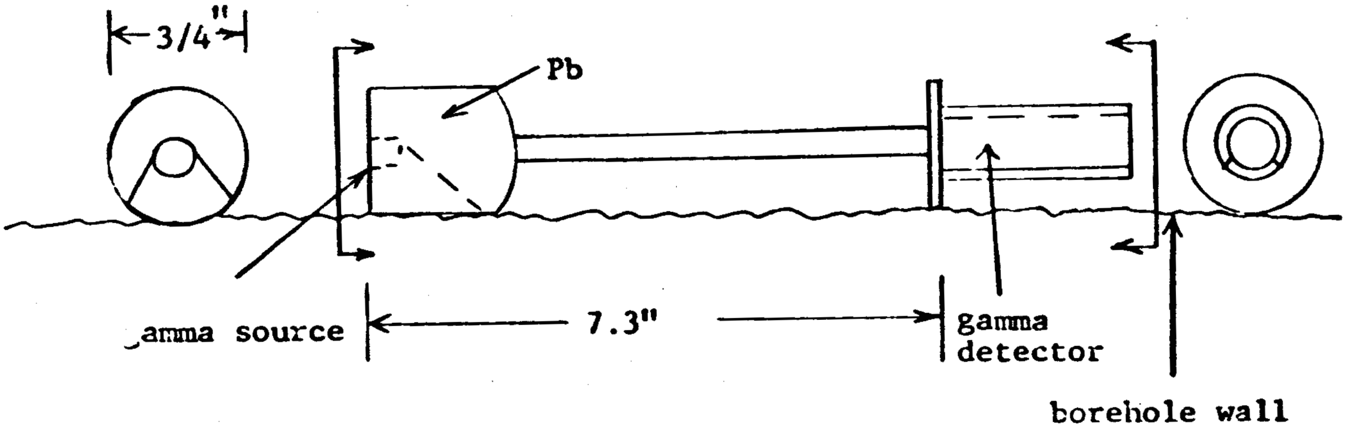

FIGURE 1.

The most practical gamma source appears to be metallic Au^{198}, which is made by neutron capture in natural Au^{197}. Au^{198} decays with a 65-hour half life and emits primarily gamma radiation having an energy of .41 MEV. Also 0.97 MEV betas are present. The beta particles would be shielded by the logging tool case. The photoelectric cross section for lead increases sharply at 0.5 MEV. In the surface package a Cs^{137} source was used which emits .67 MEV gamma radiation, and 2.35" of lead was used as a source shield. The photoelectric absorption coefficient increases by a factor of 2.3 between .67 and .41 MEV. Therefore the amount of source shielding for the same direct transmission would be less by this factor, or a 1" thickness for the source shield would be needed for the direct transmission to be the same in the downhole unit as in the surface unit. If the gamma radiation from Au^{198} is too high an energy for this amount of shielding to be practical, an Hg^{197} source could be used which emits gamma radiation having an average energy of .17 MEV and has a 65-hour half life.

The detector would preferably be a fairly thin wall Geiger counter having a high Z cathode. A bismuth coated halogen quench counter would be suitable. The weight of such a detector would be on the order of 1 oz. The total weight of the above shielding arrangement and detector would be approximately 7 oz.

The biggest difficulty using a gamma-gamma logging tool in a hole is that when the tool moves away from the borehole wall, the response increases which introduces an error in the measurement of the density. For example, an error of 100% is common for a 1" movement in liquid filled boreholes. If the hole is perfectly smooth, a logging tool may be pressed up against the formation, and practically no error will be made in the density measurement. It is necessary to position the tool and in common practice, it is pressed against the side with the unshielded side of the tool against the formation. If there are only small irregularities, then a rib may be placed on the outside of the logging tool case. This rib will hold the logging tool a fixed distance away from the wall when spring loaded on the opposite side from the rib. In general, a rib will decrease errors when the enlargement is not larger than the radial thickness of the rib and when the enlargement is longer than the axial length of the rib.

For enlargements greater than those for which a rib will suffice, the following arrangement is suggested. A sufficient amount of laboratory work has previously been done to show that the arrangement as shown in Figure 2 is quite helpful in compensating for errors in hole enlargements.

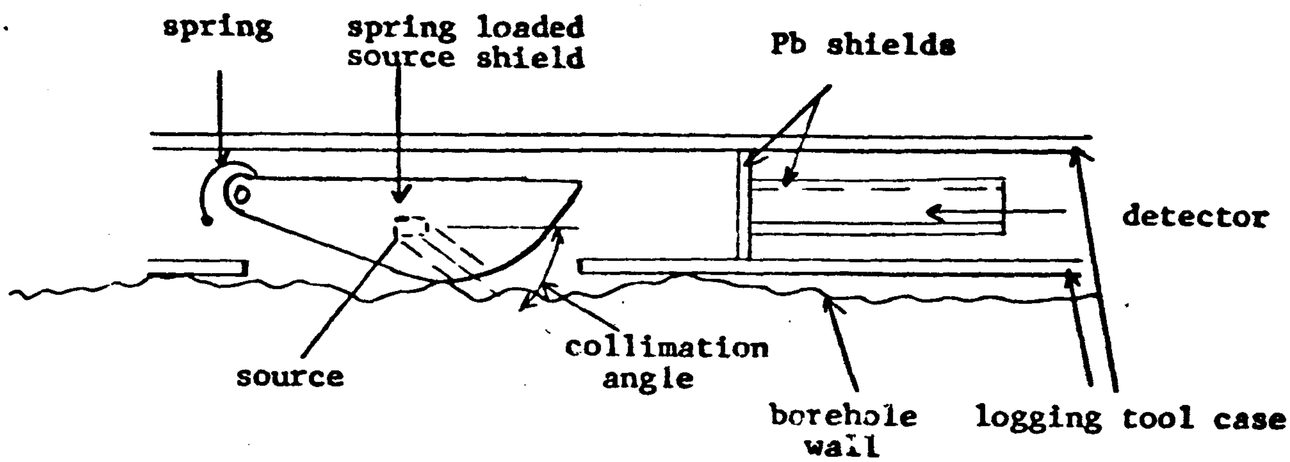

FIGURE 2

In Figure 2, as the logging tool moves away from the wall, the source shield is held touching the wall which results in (1) a collimation angle increase, and (2) a density decrease of the volume adjacent to the logging tool case. When the counter moves away from the borehole wall, the counting rate tends to decrease because (1) of the inverse square effect of the counter moving away from the wall and (2) a steeper collimation angle, but tends to increase because (1) the distance between the source and the volume of the formation from which radiation reaches the counter decreases and (2) the density of the volume near the logging tool decreases. These effects can be made to cancel over certain density ranges. It has previously been experimentally shown, that when the borehole fluid has a density of 1 gm/cm^3, that such a system will allow one to measure the density in enlargements up to 1/2 inch with an error of less than 5% in the density range from 2.0 to 3.0 $grams/cm^3$. Without such an arrangement the error is over 50%. The design of such a system requires a considerable amount of experimental work. Since the lunar hole will probably not be uniform, it seems that a density measuring device such as shown in Figure 2 would be the most desirable. The weight increase would be approximately 4 ounces, giving a total of 11 ounces for the complete density device.

The ambient temperature of the hole is unknown. It could be almost anywhere from the lower limit of the moon's surface upward. This may complicate the power supply requirements depending upon the final counter design (filling gas primarily). The operating voltage range would be 700-900 volts. The input and output requirements would be similar to those of the surface package.

A limit switch may be included for activation when the source shield is fully extended. When the limit switch is activated, the source shield would not be pressed against the wall and the density measurements would probably be in error. In this manner one would know when a density measurement is valid and when it is not valid.

B. Acoustic Measurement

In the proposed downhole measurement of acoustic velocity, it would seem practical to make a "one-receiver" velocity measurement only and to make multiple measurements with the receiver located at different depths. The source would be located on the surface at some known point, one to two feet laterally, from the top of the hole. The source would preferably be of the explosive type for the same reasons as outlined in an earlier report entitled "Measurement of Lunar Surface Acoustic Properties" (Texaco Partial Report No. 3). Also, for reasons outlined in the same report, the receiver should be of the moving coil geophone type.

It would normally be more desirable to make a two-receiver velocity measurement, as was proposed for the surface acoustic measurement. However, in this case, where it is most desirable that the sonde be a single unit structure containing other measuring apparatus, it is known from previous experience that it would be impractical to attempt to satisfactorily decouple acoustic signals traveling the short distance through the sonde itself (between the receivers or between the transmitter and receivers). Electrical pickup is a major problem in the design of such an instrument. Also, the possibility of "slowing down" the acoustic signal in the sonde path is somewhat unreasonable since its effective velocity would need to be as low as 500 ft/sec. The fact that the receiver is to be located at different depths for each "shot" partially eliminates the need for two receivers.

In conjunction with the design of the density measuring equipment in the sonde, it would be desirable that the acoustic receiver be mounted within the pivoted arm (source shield) containing the radiation source. It will be known when the pivoted arm is making physical contact with the wall of the hole, allowing acoustic coupling to the receiver. This would preferably be the highest point of physical contact between the sonde and the wall. It is assumed that the semi-rigid "cable" will not touch the wall of the hole above the sonde (the logging cable is discussed more fully in the section on complete system), or that if it does, very little acoustic energy would be transmitted down it. It should also be acoustically decoupled from the S/C and the logging tool.

The geophone should perhaps be mounted horizontally within the arm, since with the necessarily low contact pressure, the horizontal component of the acoustic signal within the arm should be greater than the vertical component.

The multiple shot source would include 6 small explosive charges which could be individually fired upon command. The source assembly would include a small somewhat flat shield with some mass (about 1 lb. weight or less), the charges to be mounted on the underside of the shield. The shield would act to direct the energy into the ground and to reduce the gas wave striking the S/C which might in turn cause acoustic energy to be propagated to the sonde by way of the semi-rigid "cable". It is believed that this acoustic energy will be of low enough level to be of little effect. Also, the time-of-travel by this path should be rather long. The feasibility of an acoustic source consisting of a dropped weight is unknown at the present time and would require additional experimental work.

Operationally, the acoustic measurement would be made by locating the sonde at a fixed and known depth, stopping all equipment which would generate background noise, detonating the small explosive at the surface and recording the time of detonation (time-break) and the receiver signal. The recording would be done with one channel. After this operation is complete, it would be repeated with the sonde located at other depths.

The downhole acoustic measurement eliminates (or reduces) at least two problems anticipated in the surface acoustic measurement. First, the gas wave from the explosive should be a less critical problem here since the lunar material offers natural shielding for the direct source-to-receiver path. Second, the only acoustic decoupling problem between the source and receiver would be for that acoustic signal which would travel the sonde "cable", a signal which should be small.

It would be desirable (but not necessary) that the sonde be oriented such that the contact arm containing the geophone be against the hole wall nearest the source. This can be done since the sonde "cable" is to be semi-rigid allowing predetermined azimuthal control of the sonde.

In order that the exact location of the source be known, with respect to the hole opening at the surface, it may be desirable to place it (the source) on the surface with a mechanical arm or rod, rather than lowering it with a flexible cable. The arm would need to be retracted after placement. This would prevent error in case the S/C attitude is different from horizontal. However, the flexible line can be usedif the attitude is known, or if the source drop is only a few inches.

The acoustic path of the "first-arrival" signal would be the straight line path between the source and the receiver if the material is homogeneous. This would allow a direct calculation of velocity since

$$V = \frac{L}{t}, \text{ where } L = \sqrt{d^2 + h^2} \text{ (See Figure 3).}$$

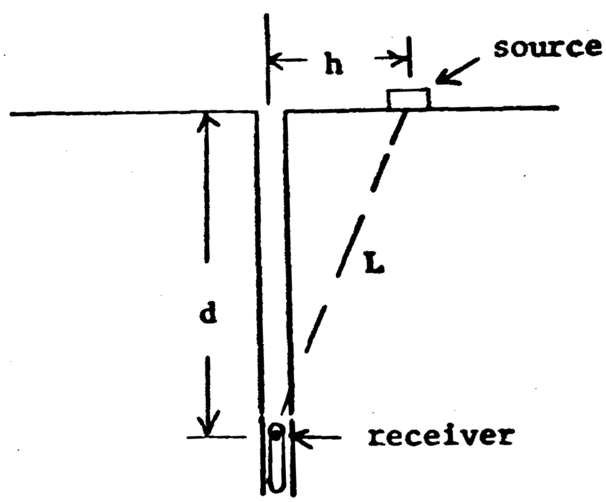

FIGURE 3

However, there will be some error in this if the material is not homogeneous. Horizontal homogenuity can be assumed. However, vertical velocity gradients are to be expected, or at least considered. A typical condition, in simplified form, is indicated in Figure 4. As indicated, the straight line path

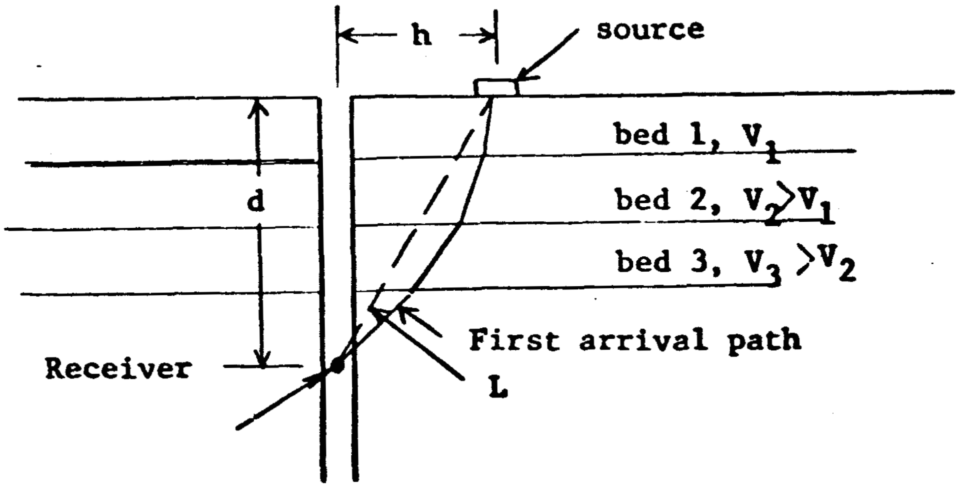

FIGURE 4

is no longer the shortest-time path. Thus, the proposed system will have inherent errors, the amount of error being dependent on the $\frac{h}{d}$ relation and the velocity gradient encountered. The subject is covered rather well by Dix[1].

The importance of accuracy in detecting the time of the detonation cannot be overemphasized in this arrangement. This, being a one-receiver measurement at relatively short spacings, will require time-break accuracy to approximately 5 µsec. It may be found necessary to place a small, relatively insensitive accelerometer on the source shield for accurate time-break detonation. However, the delay time between the electrical firing signal and firing time has recently been

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[1] C. Hewitt Dix, "Seismic Prospecting for Oil," Chapt. 7, Harper & Bros., 1952.

measured[2] to be below 2 microseconds for No. 6 caps. Thus the time break accuracy should be better than 3 μseconds.

The requirements on the data-handling equipment for this downhole system may well be more strenuous than those for the previously proposed surface measurement. Most of the requirements are the same. However, the additional variable of distance between source and receiver requires that the recording system be faster for the shallow depth shots, yet record over a long period of time for the deeper shots; i.e., with the wide range of velocities, say 500 to 10,000 ft/sec., plus the potential range of depths, say zero to 6 feet, the range of travel-times to be measured is considerably increased overthat for the surface measurement with fixed spacings. One advantage is gained in that only one recording channel would be utilized.

C. Thermal Measurements

1. Temperature

Downhole temperature will be determined by measuring the equilibrium temperature and rate of heat loss of a black body radiator suspended beneath the downhole logging tool. Radiation shields both above and below the radiator will restrict the length of borehole "seen" by the radiator. In

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[2] J.S. Rinehart and W.C. McClain, J.A.P., 31 (1960), 1809.

this way, it is hoped to minimize the temperature averaging which takes place in a cavity due to radiation interchange between the various parts of the cavity.

Heat loss in the black body radiator will be determined by measuring the thermal gradient in the support for the radiator. Final temperature determinations should be based on empirical calibration of the instrument. Thermocouples may be used to measure the temperatures involved.

2. Diffusivity

The diffusivity can be measured by monitoring the temperature rise in the black body radiator when power is dissipated in the radiator at a constant rate. Preliminary calculations indicate that dissipation on the order of 1 watt for a period of 100 minutes should be adequate to yield order of magnitude values for the diffusivity in the range 10^{-6} to 10^{-3} cm^2/sec. Calculations indicate that, when radiation is leaving a spherical iron ball of 1 cm. radius in an infinite medium whose initial temperature is 200°K, bounded internally by a spherical cavity 2 cm in radius at a rate of 6 cal/minute, more than 50% of the power supplied to the iron ball is radiated to the formation over the 100 minute period. As yet, temperature of the radiator as a function of time for constant rate of power input has not been computed, but it can be done using the solution for constant rate of power radiation. These results should be a first order approximation to the empirical calibration curves that will have to be obtained from such instrumentation.

The physics of the above downhole unit are quite similar to one of the systems proposed for measuring the diffusivity of the material on the lunar surface, namely, the method which uses an artifical light source. Therefore, basic studies of emissivities and solutions of heat flow equations would be applicable to both situations.

For accurate calibrations of temperature, diffusivity, and length of hole over which the measurements are averaged, the borehole diameter needs to be known. There will be some compensating effects present when the temperature and diffusivity are measured under conditions of a variable diameter borehole, but none for the length of the hole which the device "sees".

D. Electrical Measurements

A feasible method of measuring downhole magnetic susceptibility would be to use an arrangement of four coils as shown schematically in Figure 5.

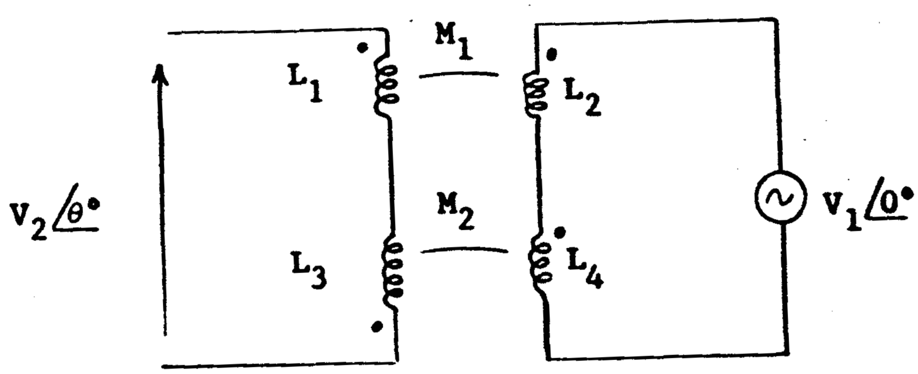

FIGURE 5

Coils L_1 and L_2 are electrically coupled by mutual inductance M_1, and coils L_3 and L_4 are electrically coupled by mutual inductance M_2. The downhole probe would be made up of only one pair of these coils, say L_1 and L_2. The other pair of coils, L_3 and L_4, would remain at the surface as a part of the surface instrumentation.

The pairs of coils would be designed so that the voltage V_2 would be zero for the probe in a given medium such as air or vacuum. As the probe is moved into a different medium, V_2 will be different from zero both in amplitude and phase with respect to V_1. The complex voltage V_2 may then be separated into two components, one at 0° and one at 90°. The 0° component would be proportional to the conductivity of the medium, and the 90° component would be proportional to the magnetic susceptibility. These measurements could be made on a bridge arrangement identical to that used in the surface measuring equipment, or by other electronic means.

It is to be emphasized that the bridge circuit is only one method of measuring the change in mutual inductance. In this particular system, the second set of coils on the surface is used as a reference. Basically, however, a single pair of coils may be used and the variation in the mutual inductance between the conditions when the pair of coils is in a vacuum and when it is in the borehole may be measured.

For the system to have a reasonable sensitivity, the probe coils L_1 and L_2 need to be of large diameter. This, of course, is not compatible with the proposed diameter of the downhole logging sonde. It was found experimentally that a fair degree of sensitivity may be achieved by winding the coils by the method shown in Figure 6.

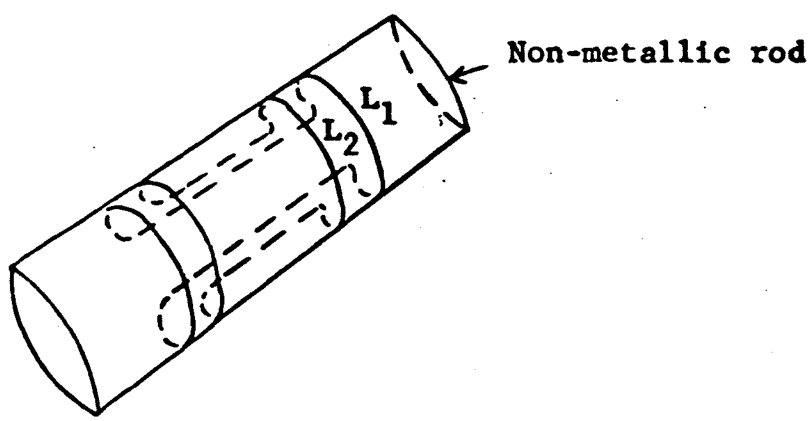

FIGURE 6

This method takes advantage of sonde length. Using the bridge, typical sensitivities obtained were a change of 50 ohms out of 15K for a susceptibility change from that of air to a ferric chloride solution having a susceptibility of 70 x 10^{-6} c.g.s. units, and 1.5 ohms out of 200 for a resistivity change from that of air to the ferric chloride solution having a resistivity of approximately 50 ohm-cm. The sensitivity for making the susceptibility measurements is satisfactory but is low for making the resistivity measurements. This point is discussed more completely later in this section.

The coil arrangement of Figure 6 does not present a symmetrical flux density. Therefore, it would be desirable to force the side of the logging tool having the highest concentration of magnetic flux against the borehole wall. The system would have to be calibrated with this in mind.

The two coils making up the probe would weigh approximately 4 ounces. The operating power and data output would be approximately the same as that of the system used to make these same measurements on the lunar surface.

One limitation is that the probe coils must not be completely enclosed by a metallic material. A second limitation would be that the distance from the coils to the formation wall should be known. No experiments were performed, but it is felt that this factor will have to be taken into account. This distance could be measured continuously by recording the position of the source shield if necessary.

Returning to the resistivity measurements, from the data given and also from the bridge balance conditions, it is obvious that the order of magnitude of the maximum measurable resistivity using the bridge balance system is on the order of 10^{-1}-10^{1} ohm-cm. This value is several orders of magnitude away from those which are thought to be present in the lunar material. Even with a redesign of the coil arrangement and bridge circuit, it is felt that the correct range will not be obtained. The reasoning is as follows.

The resistivity is measured by means of a variation of the eddy current power loss component of the total power loss in an inductive circuit. Thus the Q of an electrical system involving eddy currents, which is the ratio of the energy stored to the energy dissipated in any system, varies as the resistivity of the material in the vicinity of the electrical system. Specifically in an inductance, the Q is the ratio of the inductive reactance to the equivalent series resistance, which includes terms depending on eddy current losses, I^2R losses, dielectric losses in distributed capacitances, and skin effects. Q is related to the resistivity of the surrounding material through the eddy current losses. If the Q of the circuit is quite low, say due to large I^2R losses, then variations in the eddy current losses (which are inversely related to the resistivity) will not affect Q until the eddy current losses get large (i.e. until the resistivity is low). To be able to measure a very high resistivity, the Q of the circuit must be quite high.

In the two coil arrangement tested experimentally the Q of the system is on the order of 0.1. This figure is quite low and materials having resistivities on the order of 10^{-1}-10^{1} ohm-cm have to be present before the Q of this system is affected to any large extent(and before a measurement may be made). These resistivities are on the order of 10^5 ohm-cm lower than the lowest to be expected for the lunar material. Therefore it is obvious that the Q of the system used to measure the resistivity must be much higher than 0.1. Due to several factors, it is not advisable to raise the Q of the system used to measure the susceptibility nor is it feasible at low frequencies.

The relationship between the Q of a coil and resistivity of the surrounding material was measured experimentally using a 5/8" diameter air core coil, No. 16 wire, 10 turns, frequency = 10 M.C., capacity for resonance = 220 $\mu\mu$f, and a Boonton Q meter. A 3/4" diameter test tube was used as a simulated borehole. The results are shown in Figure 7.

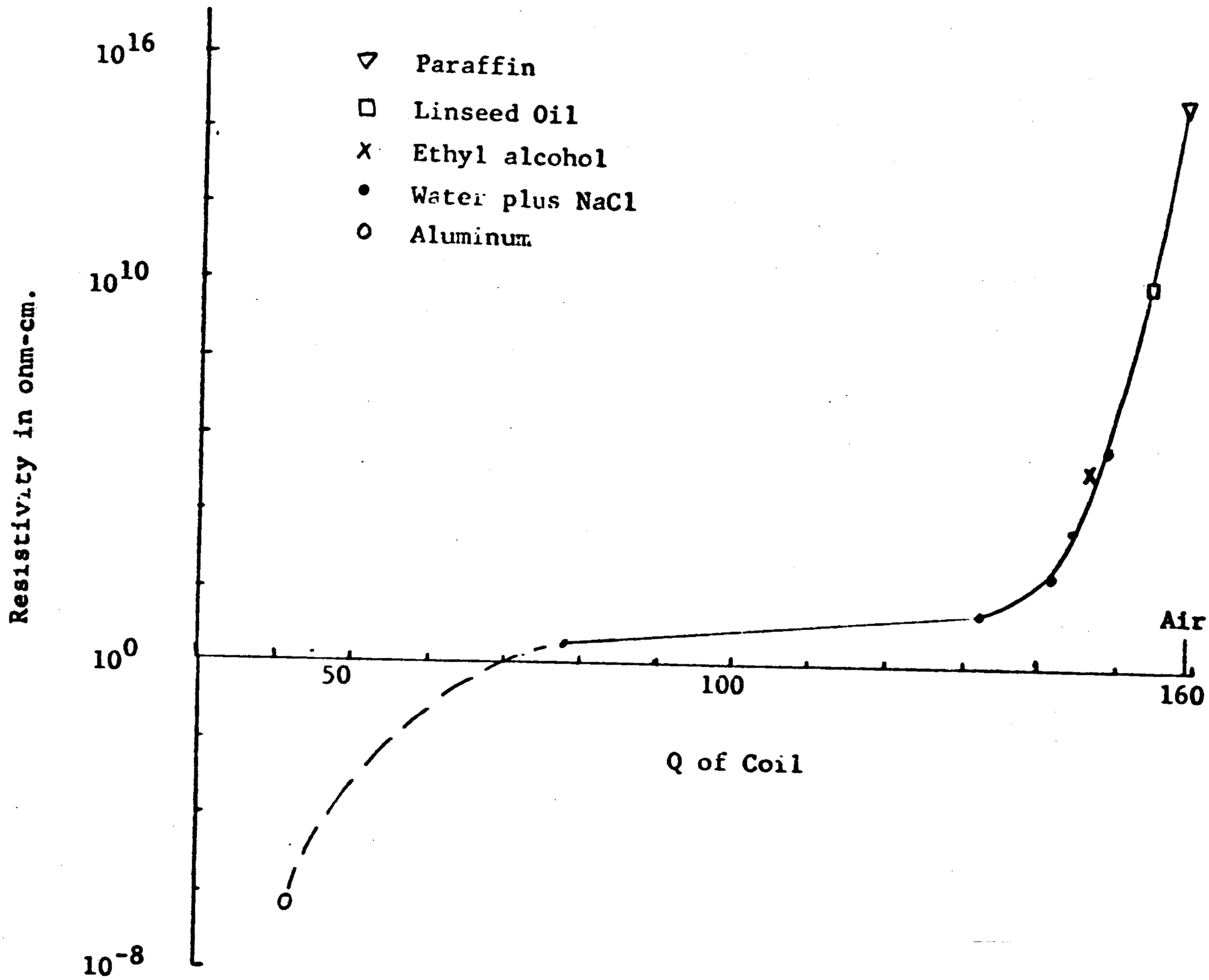

FIGURE 7

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The data of Figure 7 shows immediately that an inductive system having a Q of 0.1 would be measuring resistivities far below those of interest. It is seen from Figure 7 that above 10^{12} ohm-cm, Q does not change appreciably when using this particular coil. However, by measuring the Q of the coil in the range from 75-159, resistivity in the range 10^{1}-10^{12} could be measured ~~by~~ ~~accurately~~ measuring Q and it could be determined whether the resistivity was above 10^{12} ohm-cm. If a wider range of resistivities is expected, the Q could be made larger by using a negative resistance in series with the coil. Such techniques have been previously reported[3] in connection with the measurement of low-loss dielectrics. For low resistivities, i.e., aluminum, it is quite probable that the skin effect was affecting the values of Q. It must be remembered the Q is frequency depedent.

The system proposed for measuring the resistivity is simply to place a coil in the logging tool and measure its Q at 10 M.C., and from a curve such as shown in Figure 7, the resistivity may be obtained. This system has previously been used[4] to measure the resistivity of semi-conductor materials.

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[3] J.L. Dalke and R.C. Powell, N.B.S., Electronics, Aug. 1951, p. 225

[4] H.K. Heinsch and J. Zucker, R.S.I. 27, 409(N), (1956).

The difference in Q between that of a vacuum and the material would serve to calibrate the measurement. The weight of the coil would be approximately 1 oz.

The above system appears to be the most feasible system, but other systems have been considered. A second system which would in principle work is based on the assumption that the dielectric constant was known. This would consist of measuring the loss angle of a condenser. The tangent of the loss angle of a condenser (tan δ) is[5]

$$\tan \delta = \frac{1}{.55 \times 10^{-12} K \rho f}$$

where K = dielectric constant

ρ = resistivity in ohm-cm, f = frequency in cycles.

For resistivities between 10^6 and 10^{10} ohm-cm, assuming a dielectric constant of 5, tan δ would vary between 40 and .04. This range of values is easily measured on a bridge. In the lunar case, one could not easily get the material between two parallel plates. However, one could measure the capacitance of two of the radiation shields and possibly observe a change in tan δ for changes in the

[5]Radio Engineering, F. Terman, Third Edition, p. 24-25.

resistivity of the formation. The values of tan δ would probably be down at least an order of magnitude, i.e., the range of values to be measured would be from 4.0 to .004. This would still be measurable with 1000 cycles on a bridge as the measurable lower limit is usually taken as .0001. One could measure the resistivity separately, and using the capacitor method, measure the dielectric constant.

Other methods for measuring the resistivity were considered, but none appeared feasible. For example, a four electrode system using lead electrodes is not considered feasible due to the high contact resistance. This was proved experimentally by measuring with a megger the apparent total resistance of a 1" thick slab and a 3" thick slab of dry limestone to be the same. This indicates that the contact resistance was primarily being measured.

Also in connection with the measurement of resistivity it is recommended that the specified range of values (10^6-10^{10} ohm-cm) be reviewed. Talc and quartz have been measured[6] to have resistivities on the order of 10^{15}-10^{18} ohm-cm. Dry sand was measured by the apparatus used to take the data of Figure 7 to have a Q of 159. This

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[6]Procedures of Experimental Physics, J. Strong, p. 568.

indicates that the resistivity is above 10^{12} ohm-cm. Thus it may well be that the resistivity of the material on and near the lunar surface is well above 10^{12} ohm-cm.

E. Other Measurements

One of the more promising additional measurements which may be made is to measure the uranium and thorium content of the lunar material. The most obvious way to do this, using the present tool, is by the beta-gamma method which has previously been used[7] to measure the uranium and thorium content of ore samples. These measurements are primarily useful for uranium contents larger than .001% U_2O_3 and thorium contents above .05% thorium. Below these values, the potassium content interferes since 1% K_2O is approximately equivalent to .0007% U_2O_3. On earth the uranium to potassium ratio is relatively high and hence no trouble has been experienced. An additional solid state charged particle detector would allow a measurement of alpha particles. Using the beta-gamma method and knowing the alpha flux, one could then calculate the amount of uranium, thorium, and potassium. The above beta-gamma method is known to work quite well on earth for

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[7] G.G. Eichholz, J.W. Hilborn, and C. McMahon, Can.Jour.Phys. 31, 613, (1953)

uranium and thorium. The uranium would no doubt be in equilibrium. By including a surface charged particle detector, or by measuring with the same unit at the surface, and assuming the intensity of cosmic radiation to be constant, a measurement of the integral density could be made. This would be based on the change of charged particle intensity versus intervening material. With no atmosphere, the number of charged particles would increase for shallow depths.

The addition of a separate beta counter would increase the total weight of the logging tool by approximately 4 ounces and the overall length by 4".

Other measurements which could be made using neutrons have been covered in Texaco's Partial Report No. 4, Measurement of Lunar Parameters Using Downhole Nuclear Logging Tools.

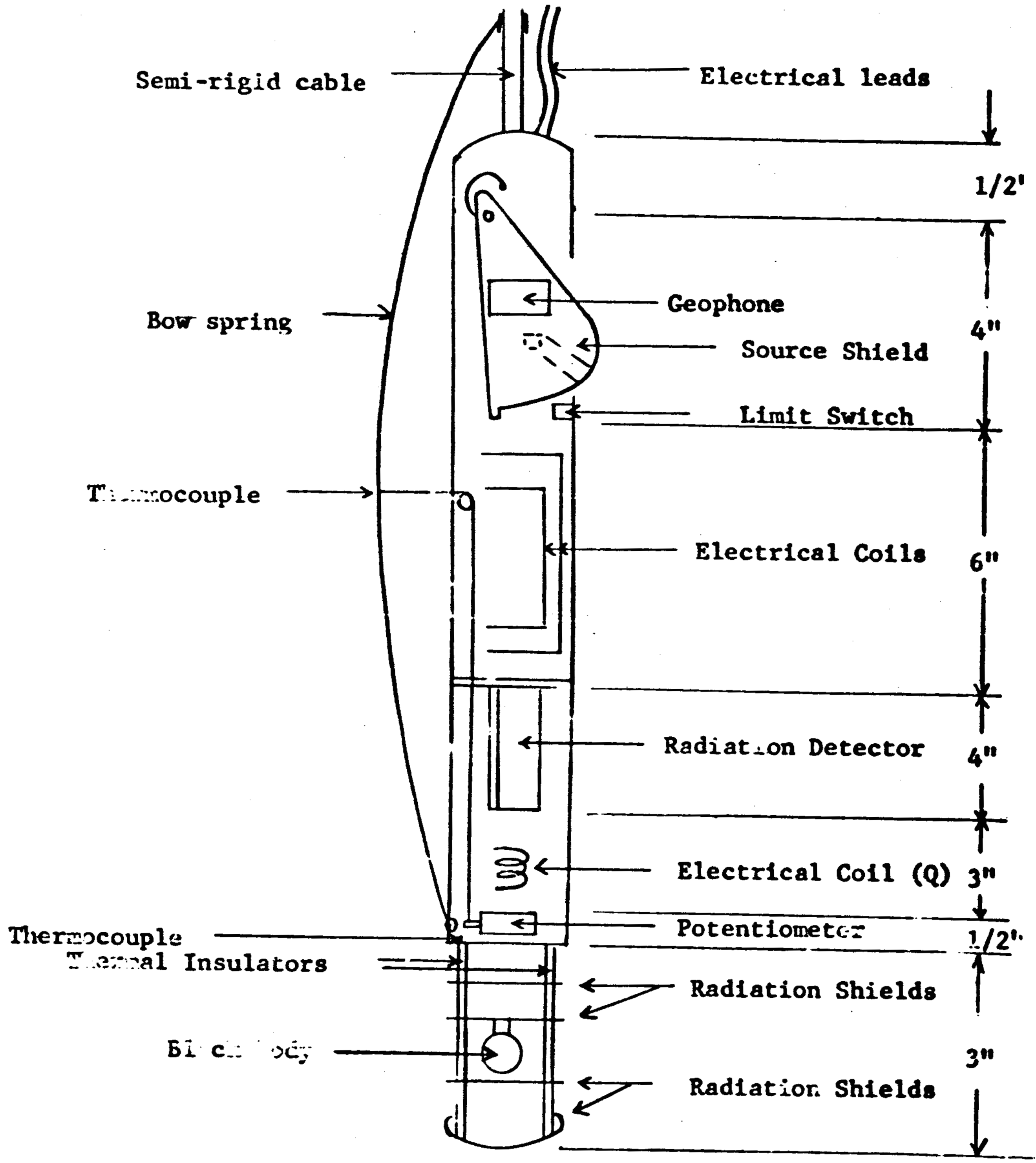
Semi-rigid cable
Electrical leads
1/2'
Bow spring
Geophone
Source Shield
4"
Limit Switch
Electrical Coils
6"
Radiation Detector
4"
Electrical Coil (Q)
3"
Thermocouple
Potentiometer
1/2"
Insulators
Radiation Shields
3"
Radiation Shields

FIGURE 8

III. Complete System

A. Constructional Details and Operation of Logging Tool

The proposed logging tool, which incorporates the suggestions of the individual preceding sections, is shown in Figure 8. Approximate dimensions are shown on this figure. The overall length is 21 inches and the tool is collapsible to a 7/8" diameter.

The tool as shown in Figure 8 will measure density, magnetic susceptibility, electrical resistivity, temperature, thermal diffusivity, integral acoustic velocity, and borehole diameter. A separate acoustic source is needed above the lunar surface to complete the velocity measurements.

As previously discussed, it is desirable to hold the tool against the borehole wall to aid in the interpretation of the data obtained from the density and electrical measuring devices. The bow spring is attached to the main body of the tool to press the tool against the formation wall. It is proposed that this bow spring is made of a non-metallic material such as Kel-F so that variations in the position of this spring will not affect the electrical measurements. It is further proposed that a thermocouple be attached to the point of contact of this bow spring with the formation. The thermocouple leads would be wrapped around a lightly spring-loaded shaft of a potentiometer. The spring loading would keep the leads taught.

The resistance value of the potentiometer (for example, 50-1000Ω) would be proportional to the hole diameter. This thermocouple would be useful if the thermal conductivity turned out to be much higher than anticipated.

The caliper log would be useful in interpreting the data obtained from the thermal, density, and electrical sensors.

The function of the spring-loaded source shield for the gamma radiation source has been previously described. The main bowspring is to exert a larger lateral force than the spring on the source shield. The lateral force of the spring loaded source shield may be small, i.e., perhaps 2 ounces. The main bowspring should then have a force of approximately twice this amount, i.e., 4 ounces. Now the moon weight of the logging tool is to be approximately 4 ounces. Thus it would be advisable to have a mechanism for exerting a downward force of perhaps 2-5 pounds on the logging tool when it is inserted into the hole. This would greatly reduce the possibility of the tool hanging up while being lowered into the borehole. The mechanism for accomplishing this could be something like a choke cable or a steel measuring tape. The electrical leads to the down hole unit could be in the form of a spiral spring-loaded cable (i.e. desk telephone receiver cable principle). This arrangement would eliminate the need for slip rings at the surface which may be quite troublesome in the lunar environment. Such an arrangement would be depth limited, but would be sufficient up to 6-8 feet of hole.

The acoustic sensor has been located near the top of the logging tool. This has the advantage that the distance from the acoustic source to the acoustic sensor would be more accurately known (since the logging tool case could furnish a path for the acoustic energy). An advantage of having the acoustic sensor located in the source shield is that it will be known whether physical contact with the formation is being made. One disadvantage of locating the sensor near the top of the tool is that approximately 18" of hole are lost. However, it is felt that the advantages of the proposed arrangement outweigh the one disadvantage.

It is noted that the tool may be raised or lowered into the borehole at any time. Thus, if desired, a continuous record of the density, electrical parameters and hole diameter may be obtained as a function of depth. The thermal parameters would in general be measured at fixed depths. The acoustic velocity would of necessity be measured with the tool at fixed depths.

The primary thermal sensor was placed at the bottom of the logging tool. Since the thermal properties are of primary importance, this was deemed desirable. Also this simplifies the corrections needed for conduction losses. The thermocouple at the lower end of the logging tool case is needed to correct for heat flowing from the black body to the logging tool case. The lowest radiation shield is a curved surface to allow for any ledges in the borehole which may tend to stick the tool.

A limit switch is shown which is activated if the source shield is fully extended. As previously indicated, when this shield is not fully extended, the density measurement would be valid but the measurement would probably not be valid if the switch were activated. One could monitor the position of the source shield with a potentiometer if deemed necessary. Such a monitor may be necessary to properly interpret the data obtained from the electrical measuring device. The sensitivity of the electrical measurements to a movement of the tool away from the formation wall should be determined experimentally. The acoustic measurement should not be made if the limit switch shown in Figure 8 is activated.

The acoustic source would be nearly identical to the source proposed for the surface measurements. It may be possible to record both the surface and downhole velocity measurements when a single acoustic source is fired with an additional recording channel.

B. Specifications of Logging Tool

The specifications, power input, data output, etc. are shown in Appendix A for a logging tool to be inserted in a consolidated borehole and for a probe to be driven into unconsolidated formations. The power requirements and data outputs are quite similar to those of the surface measurement package.

C. Instrumentation to be Driven Into Unconsolidated Materials

The condition that the lunar material is unconsolidated needs to be considered. Under this condition, it is quite likely that it will be impossible to drill a consolidated hole. Also under this condition, it would be advantageous to have a probe which could be forced into the lunar surface to a known depth.

Using the logging tool shown in Figure 8, there would be at least two possible methods of approach. One method would be to build the tool as shown in Figure 8, with some modification of the lower end such as a conical bull plug made of a low heat capacity material, sufficiently sturdy so that it could be forced into the lunar material. A second approach would be to encase the logging tool shown in Figure 8 inside a second case. The second case would have a sharp pointed bull plug. The unit would be forced into the material applying the necessary force to the second case. After reaching the desired depth, the second case would be disengaged from the bull plug and retracted leaving the bull plug and the logging tool in the lunar material.

The second approach would definitely work although it would require more manipulations. The first approach may be feasible due to the fact that the materials used in the construction would be in compression. A dummy unit was made of aluminum which had a conical bull plug and five radiation shields.

No difficulty was encountered in forcing this unit into loose dry sand or salt. The .006" thick simulated radiation shields were undamaged after driving the probe into clean dry sand ten times to a depth of 18".

Thus it would appear that a probe could be built very similar to the one shown in Figure 8 but with a conical bull plug. The bull plug would have to have a low heat capacity and its temperature should be monitored. It was interesting to note that the force required to force the probe into dry sand was surprisingly small, namely 50 pounds. It is felt that the force would have been much greater if the sand had been wet.

IV. Conclusions

This feasibility study has shown that the density, magnetic susceptibility, electrical resistivity, integral acoustic velocity, temperature, and thermal diffusivity of the lunar material along with the hole diameter, could be measured in a consolidated borehole with a downhole logging instrument weighing approximately 34 ounces having a diameter of 7/8" and a length of approximately 21 inches. The tool could be raised and lowered in the borehole. An acoustic source would necessarily be on the surface. The input power required and data output from the various sensors would be almost identical to those of the surface package. The downhole unit is adaptable to being slowly driven into an unconsolidated material. By the addition of slip rings the unit would be adaptable to log much deeper holes than the 6-foot hole considered in this study.

Bellaire, Texas
December 12, 1960

APPENDIX A

Instrumentation Subsystem for Operation Beneath Lunar Surface

1) General Functions and Dimensions

Covers instrumentation subsystem for downhole use or to be slowly driven into lunar surface. Weight estimates are for instrumentation system only and do not include hole making or driving mechanism.

a. Density Measurements. Utilizes the method of gamma-gamma logging wherein a partially shielded radiation source is placed a known distance from a partially shielded GM Counter. The logarithm of the detected gamma radiation is inversely related to the density of the lunar material. Background levels are monitored after the 65-hour half life gamma radiation source has decayed to a negligible value.

b. Acoustic Velocity Measurement. The integral compressional velocity between the lunar surface and the point of contact of the logging tool to the borehole wall is calculated from measured distances and acoustic travel times measured using a small explosive charge as the acoustic source on the lunar surface and a geophone as the acoustic sensor in the down hole unit. The distance from the acoustic sensor to the acoustic source must be known.

c. Magnetic Susceptibility Measurement. The technique proposed, which has been demonstrated experimentally, is to measure the change in mutual inductance of two coils between the conditions of air (or vacuum) and within the hole. A mutual inducatance bridge of the Carey-Foster type is one method of measuring this change in the mutual inductance. The difference in the mutual inductance under the two conditions is proportional to the magnetic susceptibility of the lunar material through which the hole penetrates.

d. Electrical Resistivity Measurement. Utilizes variation in Q technique for measuring resistivities. The Q of a coil decreases as the resistivity decreases due to an increase in the eddy current losses. This has been shown experimentally and the method has previously been used.

e. Thermal Measurements. The principal quantities of interest are the temperatures at various depths within the borehole, the thermal conductivity and diffusivity at various depths within the borehole, the vertical temperature gradient with reference to the lunar surface, and the lateral temperature gradient with reference to the borehole wall. Because of the low expected thermal conductivity and due to difficulties encountered in obtaining meaningful temperature measurements using sensors which require mechanical contact under this condition, a radiation device is proposed. This device consists of a spherical black body suspended within the borehole with radiation shields above and below the black body. By measuring the temperature of the black body and the amount of heat transmitted by conduction through the mounting structure into the blackbody radiator, reasonably reliable temperature measurements may be made at various depths. By following the heating (and/or cooling) curve of the black body when it is heated by an internal heat source, the thermal diffusivity of the formation may be measured. Both the temperature and diffusivity measurements made in this manner will be averages over 1-3" of the vertical dimension of a consolidated borehole.

f. <u>Hardness Measurement</u>. The rate of penetration of the drill will be related to the "drillability" of the lunar material which in turn is related to the hardness. In the case of unconsolidated materials, the force necessary to force the probe into the material would be related to the hardness.

g. <u>Caliper</u>. The lateral travel of a decentralizing bowspring on the logging tool is monitored using a wire around a variable spring-loaded potentiometer.

Note: Overall dimensions of downhole logging tool: Collapsible to 7/8" diameter by 21" long (See Figure 8). Acoustic source and shield for six shots consists of source 0.5" in diameter and 2" long with attached shield 3" by 2" by 1/8".

2) Environmental Requirements

a. Operating Environment. The subsystem is designed to survive the lunar environment as specified in TM 33-13 with the following additional constraints.

(1) Radiation environment allowed at GM Counter used in density measurement to be less than 500 gamma quanta/cm^2/sec. and less than 15 electrons (energy >1 MEV)/cm^2/sec.

(2) D.C. Magnetic field to be less than 0.25 gauss. A.C. Magnetic field to be less than .001 gauss.

(3) Operation with density GM Counter above 150°K.

b. Nonoperating Environment. The subsystem is designed to survive the lunar environment as specified in TM 33-13.

3) Weight Breakdown

a. Density - 11 ounces.

b. Acoustic Velocity - 2 ounces plus weight of acoustic source.

c. Magnetic Susceptibility - 4 ounces.

d. Resistivity - 1 ounce.

e. Thermal - 6 ounces (includes thermocouples, radiation shields, black body, and supports.

Note: Probe structure weight (excluding leads and supports from logging tool to S/C)- 10 ounces.

4) Total Weight

a. Thirty-four ounces for downhole probe (excluding leads and supports from logging tool to S/C.)

b. Acoustic sources and shield - 1 lb.

c. Thirty-six ounces for slowly driven probe (excluding leads and supports from probe to S/C).

5) Required Orientation

a. In consolidated hole. Vertical Alignment of logging tool and lowering into hole. Radiation source shield, when extended, to be in direction of acoustic source within ±15°.

b. In unconsolidated material. Vertical alignment of probe and slowly driven into surface to depth of 21".

6) Required Knowledge of Orientation

a. In consolidated hole. Must know whether or not probe is in borehole. Depth of logging tool with respect to acoustic source to be known within 0.5". Depth of logging tool with respect to lunar surface to be known within 0.5".

b. In unconsolidated material. Depth known to 0.5", vertical alignment to ±10°.

7) Operating Power

a. Density

(1) 0-10 microamps drain.

(2) 800 volts d.c. regulated.

Range - 700-900 volts d.c.

Tolerance - ±2%.

Ripple - Tolerance depends on type of supply.
At 60 cycles, 10 volts ripple is acceptable.
In KC range or above, ripple to be less than 0.1 volt.

(3) Power supply output impedance - less than 1000 ohms.

b. Acoustic Velocity - None except power to detonate acoustic sources.

c. Magnetic Susceptibility. The following are needed if Carey-Foster bridge used:

(1) 70 milliamps

(2) 90 volts

Range - 90 $^{+50}_{-25}$ % volts a.c.

Tolerance - 15 ±5% volts a.c.

(3) 300 ohms input impedance to bridge.

(4) 1000 cycles ±25% but known well enough to be compatible with data output.

(5) Distortion of a.c. to bridge - less than 0.005%.

d. Resistivity - Need to measure Q of coil at frequency of 10 ±1 M.C. Q varies from 50 to 250.

e. Temperature - None.

f. Diffusivity - 1 watt, either a.c. or d.c. power used to heat resistor, peak voltage less than 300 volts.

g. Caliper - Power to measure resistor value in range of 50-1000 ohms.

8) Time per Operating Period

a. Density - 3 minutes.

b. Acoustic Velocity - 1 second (starting at time of detonation of acoustic source).

c. Magnetic Permeability - 60 seconds (time to balance bridge and record resistance; if bridge not used, depends on how the mutual inducatance is measured).

d. <u>Resistivity</u> - Approximately 1 second (time to measure Q of coil; length of time will depend on method used to measure Q).

e. <u>Temperature</u> - Continuous sensor operation.

f. <u>Diffusivity</u> - 120 minutes.

g. <u>Caliper</u> - 1 second.

9) <u>Number of Operating Periods</u>.

(Based on 6' deep hole, and one repeat obtained of each measurement, and measurements made at depths shown in 15)a(6).

a. <u>Density</u> - 48 plus 48 monitor periods.

b. <u>Acoustic Velocity</u> - 6

c. <u>Magnetic Susceptibility</u> - 96

d. <u>Resistivity</u> - 96

e. Temperature - 48 with continuous sampling during day/night and night/day transistions (3 hours centered around sunset and sunrise).

f. Diffusivity - continuous recording of temperature of black body for 30 minutes prior to heating of black body sphere, 60 minutes during heating, and 60 minutes after heating. 24 cycles required.

g. Caliper - 96

10) Sample Preparation Requirements - None

11) Manipulation Requirements

a. Alignment of logging tool over borehole, raising and lowering of logging tool in and out of borehole.

b. Placement of acoustic source.

12) Data Output

a. Density - 2 volt negative pulses of 50 µseconds duration, 50-1000 c.p.s. load impedance of 500K ohms, range 100K to 1 megohm. An accuracy of ±5% in the density data received on earth is required.
Measurement range - 0.5 to 4 gm/cm^3.

b. Acoustic Velocity - 10 microvolts to 1 millivolt. (50 cycles to 5KC). 300-ohm output impedance.
1 microvolt is maximum allowable peak-to-peak noise in input to recording system. Wave form is desired.
Measurement range - 300 to 20,000 ft/sec. Accuracy of data received on earth is to be ±10% in lower velocity range and ±20% in upper velocity range.

c. Magnetic Susceptibility - Mutual inductance change. Measurement range (susceptibility) 10-50,000 x 10^6 c.g.s. units. Required accuracy of data received on earth is ±25%.

d. Resistivity - Q change. Q ranges from 50 to 250 at 10 M.C. Measurement range - 10^{-6}-10^{10} ohm-cm.

Required accuracy on earth, ±0.4% of magnitude of Q.

Note: Output data for magnetic susceptibility and resistivity measurements depend on method chosen by S/C designer to measure mutual inductance change and Q. If use Carey-Foster bridge, bridge characteristics are:

R_1 = 0-1000 ohms, steps of .05 ohms ±3%, linear pots.

R_2 = 100 ohms, ±1%.

R_3 = 0-80,000 ohms, steps of 1.0 ohms, ±3%, linear pots.

C = .01 microfarad, ±5%.

e. Temperature - 0.3 to 0.8 millivolts per degree K. 150 millivolts is total range and there is no bias. Recovery of data on earth to 0.3 millivolts is required. Temperature reference required. Four sensors. Measurement Range - 120° to 400°K.

f. Diffusivity - 0.3 to 0.8 millivolts per degree K. 250 millivolts is total range, no bias. Temperature reference required. Measurement Range: 10^{-3}-10^{-6} cm^2/sec.

g. Hardness - Record depth of drill versus time. Accuracy 10%.

h. Caliper - Resistance change, 50-1000 ohms.
Measurement Range - 7/8" to 4".

13) Real Time Data Requirements - None.
Data storage is acceptable if accuracies of magnitudes and times (specified in 12) are maintained. Time accuracy required for acoustic measurement is ±3 microseconds on time of firing acoustic source, and 5 microseconds uncertainty in arrival time at acoustic sensor.

14) Commands Required from S/C.

a. In consolidated hole:

(1) Positioning logging tool over hole.

(2) Lowering and raising of logging tool vertically within hole.

(3) Triggering of each acoustic source.

(4) Initiation of data sampling and storage.

b. In unconsolidated formation:

(1) Driving probe into material.

(2) Same as a. (3) and a. (4).

15) Operational Sequence

a. In consolidated borehole.

(1) Placement of acoustic source.

(2) Orient probe over hole

(3) Position tool in space above lunar surface and below S/C. Record depth.

(4) Record reading of various sensors.

(a) Balance bridge - 30 seconds

(b) Measure Q - 1 second

(c) Record density - 3 minutes

(d) Record thermocouples - 3 seconds

(e) Record caliper - 1 second

(f) Record limit switch - 1 second

Note: Record (a) and (b) separately, others may be recorded simultaneously.

(5) Lower tool to total depth - record depth.

(6) Record readings of various sensors.

(a) Balance bridge 30 seconds, 3" depth increments.

(b) Measure Q - 1 second, 3" depth increments

(c) Record density - 3 minutes, 6" depth increments.

(d) Record temperature - 10 minutes, 6" depth increments. If black body temperature is not stable within .1°K/minutes, continue recording until this stability is recorded.

(e) Record caliper - 1 second, 3" depth increments.

(f) Record limit switch position (activated or unactivated) - 1 second, 3" depth increments.

(g) Record depth of tool - 1 second, continuously.

(h) If limit switch not activated, fire acoustic source - record sensor output for 1 second - 1' increments.

(7) Repeat steps (3), (4), (5), and (6). If repeat, data is within allowed limits, proceed to (8). If not, repeat steps (3), (4), (5), and (6) until repeat is obtained. Additional repeats necessary only for those items which did not originally repeat.

(8) Repeat steps (3) and (4). Lower tool to a depth of the previous position plus 3". Repeat those items of (6) which are applicable at this depth. Do this complete step twice at same depth.

(9) If data repeats within allowed limits at same depth, repeat (8) at new depth until tool is out of hole.

(10) Return to bottom, check that temperature stability is greater than .1°K change/minute. Measure diffusivity. 120 minutes total time. Record temperature of black body while heating 60 minutes and cooling 60 minutes. 6" depth increments.

(11) Repeat (10). If data repeats, proceed to next highest depth. If data does not repeat, do until data does repeat.

(12) Repeat steps 3-10 during alternate day or night cycle.

(13) Stop all measurements between day/night cycle minus 3 hours. Position tool at 24" depth. Record temperatures for six hours.

(14) Same as (13) for night/day transistion.

(15) After 10 days, measure density background. If possible make all measurements, particularly electrical, both in day and night cycle.

b. Slowly Driven Probe

1. Vertical Orientation of probe.
2. Repeat step 15)a.(3) and (4).
3. Force probe into surface to a minimum depth of 21 inches.
4. Repeat step 15)a.(6) five times. Measure diffusivity 3 times.
5. Repeat steps 15)a.(1) and 15)a.(13).

16) Other Requirements

a. Acoustic decouple probe from S/C.

b. Maximum force on slowly driven probe, 500 pounds.

c. S/C acoustically quiet during acoustic measurements.

d. Know distance between acoustic source and acoustic receiver.

e. When logging tool in vacuum above surface and below S/C, nearest magnetic material to be 10" from coils in logging tool.

f. Do not activate acoustic source if limit switch activated.